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Quantifying long-term rates of texture change on road networks

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ABSTRACT

Texture is required on pavements to provide safe and comfortable ride performance for ~~road~~ users. This paper provides the first meaningful analysis of a long-term study of texture data obtained using TRACS (TRAffic Speed Condition Survey)~~ over a 24-year period,~~ at a site in the UK. TRACS data were collected annually, ~~at 10 m intervals~~ over a 2 km stretch of motorway from 1995 to 2019. A new data analysis approach utilising time series data with spectral analysis and spatial filtering procedures is presented. The results reveal that the approach enables legacy TRACS laser profile Sensor Measured Texture Depth (SMTD) data to be used to determine long term rates of change in road surface macrotexture. Thus, the technique has unlocked the potential for SMTD data collected annually for 7000 km of the Strategic Road Network in the UK, to inform ~~essential~~ road maintenance programmes by extrapolation. Additionally, results expose a systematic periodicity occurring each year within the SMTD data studied, corresponding to longitudinal oscillations with wavelengths between 33 and 62 m. The time-invariant periodicity of these oscillations suggests that it is 'imprinted' in the early life of the pavement. 'Imprinting' may theoretically arise ~~occur~~ with ~~as a consequence of either~~ cyclic tyre loading applied by the suspension systems of heavy vehicles or during road construction **[Q1]**.

KEYWORDS

- Pavement texture
- macrotexture
- skid resistance
- TRAffic Speed Condition Survey (TRACS)
- Sensor measured texture depth (SMTD)
- friction

1. Introduction

Road surface texture is essential for the safe and effective operation of road networks (Meegoda and Gao 2015). Texture influences noise and vehicle rolling resistance and by that fuel consumption and carbon monoxide emissions (Ejsmont et al. 2017, Hong et al. 2018). Texture also contributes to wear, with texture measurements taken from road networks helping to inform when maintenance is required (Meegoda and Gao 2015). The texture components of a highway surface have been characterised at four increasing wavelength scales: megatexture and unevenness, macrotexture and microtexture (International Organization for Standardisation 2009). Megatexture relates to wavelengths between 63 and 500 mm and amplitudes of between 0.1 and 50 mm, unevenness is characterised by wavelengths between 0.63 and 50 m. Highway pavement megatexture and unevenness is known to impact ride quality and driver comfort (Loprencipe 2019). Microtexture and macrotexture influence skid resistance and the friction available at the interface between the tyre and the road (Moore 1975, Klüppel and Heinrich 2001, Persson 2001). Macrotexture represents the texture with wavelengths between 0.5 and 50 mm and amplitudes of between 0.1 and 20 mm (formed by the shape, size and gradation of road aggregates on a pavement surface). Microtexture represents the asperities on the surface of road aggregates and has wavelengths up to 0.5 mm and amplitudes in the range of between 0.001 and 0.05 mm. Skid resistance on a pavement surface is essential for vehicle safety and is also affected by temperature, presence of contaminants, speed and tyre tread thickness (Kane and Edmondson 2018). The preservation of adequate pavement texture is achieved by a regime of monitoring and maintenance undertaken by road agencies; national practices vary, but data are typically collected at least annually (Design Manual for Roads and Bridges 2008, European Collaborative Project 2014). Generally, at road network scale unevenness, megatexture and macrotexture are monitored at traffic speed, using laser profile sensor techniques and video cameras mounted on specialist survey vehicles (Meegoda and Gao 2015). Microtexture which influences skid resistance at low speeds (Cunto and Branco 2016) and requires contact between a tyre tread and the surface asperities of road aggregates, is monitored using contact techniques. At the road network scale these contact techniques frequently used a fixed or braking test wheel, which measures the frictional contact at traffic speed made with the wheel and a wetted highway pavement. Kogbara et al. (2016) provide a full summary of contact devices and their operating principles.

Road infrastructure assets represent the largest capital assets of most countries (Organization for Economic Co-operation and Development 2001). The pavement geometry data obtained from surveys is commonly held in a pavement management system (Meegoda and Goa 2015) and made available to government authorities, road agencies, asset managers, engineers, and suppliers to enable them to reach decisions on road pavement maintenance priorities and programming. The aim is to provide the road user with a reliable level of service and ride safety (Transport Research Board 2016). Maintenance planning presents to the stakeholders two key fundamental challenges: the identification of locations on a large road network requiring investigation, and the deterioration characterisation of these locations to facilitate timely, appropriate and effective maintenance approaches. Furthermore, characterising suitable intervention engenders the additional challenge of judging when preventative maintenance is required, which typically offers lower cost repair options to extend pavement life, and when full resurfacing is needed. Pavement texture changes over time, these variations have previously been characterised into 'long-term variations' and 'short-term variations' (Vaiana et al. 2012). 'Short-term variations' have been established to arise due to meteorological conditions such as temperature and rainfall (Masad et al. 2009). 'Long-term variations' are given to be predominantly due to traffic actions (Viana et al. 2012). Traffic flow has a significant influence on the evolution of pavement texture (Plati and Pomoni, 2019) and as a result maintenance planning. Pavement texture deterioration has been shown to be influenced particularly by the percentage of heavy goods vehicles in a trafficked lane (O'Brien and Haddock 2009, Ragland et al. 2010, Khasawneh *et al*. 2016). Recently, an inverse trend between skid resistance and pavement macrotexture deterioration has been identified, associated with a minimum cumulative traffic threshold (Plati and Pomoni, 2019). With trafficking, macrotexture evolution was found generally to increase by Plati and Pomoni (2019) and skid resistance to reduce after the minimum cumulative traffic threshold. The threshold was given to mark the point where sufficient polishing of fine aggregates had occurred, resulting in the coarse aggregates dominating skid resistance. Hence, routes with higher volumes of traffic are likely to require prioritisation in maintenance planning. Due to the complexity of the interaction of traffic flow and meteorological conditions with pavement materials, the final decision on intervention is left to the judgement and experience of the road manager after a visual inspection.

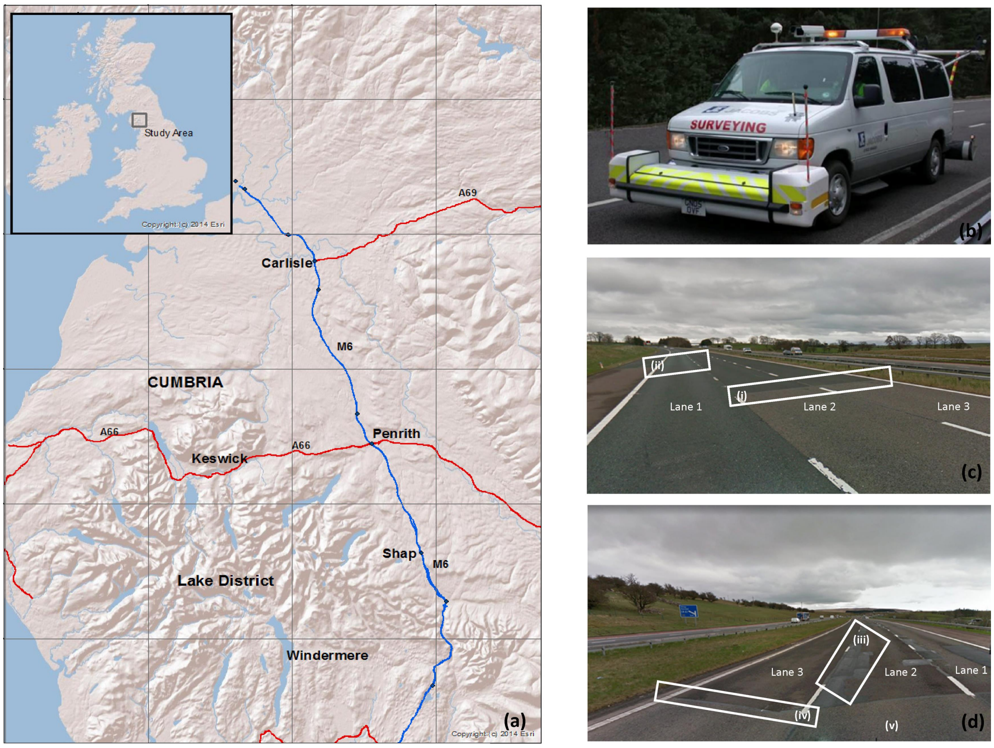
Pavement condition and performance indices that support the decision making process are based on analysis of the survey data held within the pavement management system (FSV-Austrian Transport Research Association 2008). For longitudinal pavement texture there are a number of accepted pavement condition indices utilised across the world. The International Roughness Index (IRI) models the virtual response of a 'golden car' travelling at 80 km/hr on a road profile [Sayer et al. 1986, ASTM International 2015, European Committee for Standardisation 2017]. The 'golden car' is a simulated system utilising standardised values for the damping, springs and masses relating to a portion (or a quarter) of a car supported upon one wheel, often termed the quarter-car. IRI represents the dimensionless ratio, of the accumulated vertical motion of the 'golden' quarter-car's suspension, divided by the distance travelled; known as the evaluation or segment length. Acceptable IRI threshold values are specified on a country by country basis for new, reconstructed or rehabilitated roads. Depending upon the country of application, these IRI thresholds are reported either as a constant value for an evaluation length, the average value of a series of segments within an evaluation length, or as a percentile. The evaluation or segment lengths typically vary from 10 to 1600 m. Furthermore, the IRI thresholds can be specified by a country as a function of the road surface type, category (e.g. motorway or minor road), speed limit or traffic flow. Mucka (2017) provides a full summary of the IRI specifications used around the world. Another approach to the characterisation of longitudinal road profiles is presented in ISO 8608 (International Organization for Standardization 2016). The ISO 8608 standard provides a description and classification of synthetic road profiles for use in computational modelling, based upon vertical displacement power spectral density (PSD). PSD is represented on a logarithmic scale and is defined by two parameters of a straight line: an unevenness index and waviness. The road classifications presented in ISO 8608 are primarily used for vibration modelling and are not directly linked to real road categories, although some research has been completed to derive validation (Mucka 2018). Within the UK, texture threshold values are adopted to define minimum advisory road texture levels in relation to both longitudinal profile (with an evaluation length of 100 m) (Design Manual for Roads and Bridges 2008) and also skid resistance (Design Manual for Roads and Bridges 2015). The specification of threshold values is based upon road condition and road category, with areas found to be below advisory levels prioritised for visual inspection by a road manager.

A limitation of the pavement condition indices reviewed, is the sensitivity of the techniques to the evaluation length (Transport Research Laboratory 2006). The selection of evaluation length defines the granularity of the texture data. This can be illustrated by a simple assessment of texture level against a minimum threshold. In such a case where pavement texture is averaged over a long length which contains sections of localised texture variability, the averaged result will smooth the texture data, potentially masking the true condition of shorter lengths. Stakeholders evaluating road texture for maintenance, require confidence in the deployment of follow-up resources for visual inspection and condition assessment. A preferred approach is to augment pavement condition indices with a method to track and understand the rate of change of texture condition at every location on a real road network. This would support the identification of deteriorating sections of the road network; but to date the rate of change for pavement texture at discrete locations on a real road network has been difficult to estimate reliably (Rainsford and Parkman ND). Today, access to 'big data' (Mauro *et al.* 2016 **[Q2]**) in the format of pavement management systems containing historic pavement geometries, and advances in data processing techniques means that data can now be analysed in new ways. This paper presents a new method to analyse legacy Sensor Measured Texture Depth (SMTD) (Transport Research Laboratory 2006) legacy data obtained using the TRAffic Speed Condition Survey (TRACS) system in the UK (Department for Transport 2019) and stored in the Highways England Pavement Management System (HAPMS; UK Government, 2019) over 25 years for 7000 km of Class A highway. A novel data processing approach utilising time series data with spectral analysis and novel wavenumber filtering procedures is presented, producing a rare long-term evaluation of the rate of texture change on real road networks.

2. Selecting the site and legacy data

The study site was a 2 km length of the northbound route of the M6 motorway located within Cumbria, UK Figure 1.

Figure 1. Field Site Location and Equipment: (a) The field site. (b) TRACS (TRAffic Speed Condition Survey) road survey equipment. (c) Photograph of the field site at chainage 1480 m looking northwards, clearly depicting the construction joint (e.g. i) in Lane 2 and 3 and the construction joint at 1500 m in Lane 1 (e.g. ii). (d) Photograph of the field site at chainage 600 m looking southwards, showing localised patched repairs (e.g. iii); a construction joint across (e.g. iv) all three lanes and the change to thin surfacing material (e.g. v).



The route, a predominantly straight section of rural link motorway is typically at 300 m above Ordnance Datum with some gentle longitudinal undulations. The three northbound lanes climb uphill at a maximum gradient of 3% between chainages 600 and 1500 m and are at an downhill incline of a maximum gradient of 3% between chainages 0 m to 600 and 1500 to 2000 m. The nearest traffic counter to the site operated by the country's roads agency, Highways England, held traffic data for a six-year period from 2011 to 2016. These data revealed no significant fluctuation in traffic flow for that period, with an overall mean average 24 h traffic flow of 17652 AADT one-way and overall mean percentage of large vehicles of 23.19%. The texture data relate to Lane 1 the nearside lane and Lane 2, the middle lane of the three-lane motorway. For Lane 1, the test section of road was constructed originally of dense bitumen macadam (DBM) laid on 11th October 1970. On the 27th August 2004 the DBM was replaced with heavy duty macadam (HDM) between chainage 0 and 600 m. This surface was replaced again on the 1st October 2016 as part of a resurfacing of the lane between chainage 0 and 1500 m with a thin mastic asphalt (Manual of Contract Documents for Highway Works 2019). Finally, on the 3rd March 2008, a thin polymer surfacing was laid between chainage 1500 and 2000 m (Manual of Contract Documents for Highway Works 2019). In Lane 2, the test section of road was constructed from thin surfacing (Manual of Contract Documents for Highway Works 2019) laid on 27th August 2004 for chainage 0 m to 600 m, hot rolled asphalt (HRA) laid on 5th April 1998 between chainage 600 m and 1480 m, and older HRA laid on 11th October 1970 chainage 600 m to 2000 m. Road texture data for the pavement surfaces were captured using TRACS (refer to Figure 1(b)), a purpose built road surface survey vehicle (Department for Transport 2019) over a 24-year period. The data were collected on behalf of Highways England as part of the annual maintenance survey of the UK Strategic Road Network, which encompasses the Class-A (Department for Transport 2012) principal motorways and all-purpose trunk roads within England (Highways England 2019). The TRACS vehicle was calibrated in accordance with the UK standard (Department for Transport 2019), to safeguard the quality of data during the stages of data collection, storage and extraction for post processing. The TRACS texture data were obtained at a traffic speed 50 km/h using laser triangulating profile sensors (Zhang et al. 2018). The texture data were measured by TRACS in a 300 mm wide swath, positioned over the nearside wheel track of the lane being surveyed, collecting profiles at approximately 1 mm longitudinal intervals. The TRACS survey vehicle utilises an inertia-corrected global positioning system (GPS) data in conjunction with distance measurements, to reference the location of a texture reading to a longitudinal accuracy of ± 1 m.

3. Data processing method

The raw texture depth data reported by TRACS was pre-processed by Highway Agency's Machine Survey Pre-processor (MSP) software to report the SMTD (Transport Research Laboratory 2006, Department of Transport 2019). The MSP software prefiltered the raw texture data to remove the effect of vehicle bounce and any random noise signals. The standard deviation of the filtered texture data was then calculated for each 300 mm evaluation length by the MSP software; before being aggregated to calculate an average texture height for all the evaluation lengths within a 10 m length. The averaged texture height was reported as the SMTD and stored within HAPMS, and essentially represents the root mean square measure of texture depth, both above and below the mean level for a 10 m section. The SMTD is distinct from the mean profile depth (International Organization for Standardization 2019), which measures the height of the highest peak above the mean level. SMTD is used in the UK for texture reporting and has been previously found to be related to MPD by the relationship:

$$\hbox{MPD}\, = \, 1 .4\, \hbox{x}\, \hbox{SMT}\hbox{D}^{ 0 .840}\quad {\rm \; }\lparen{\hbox{Transport}\, \hbox{Research}\, \hbox{Laboratory}\, 2006} \rparen$$

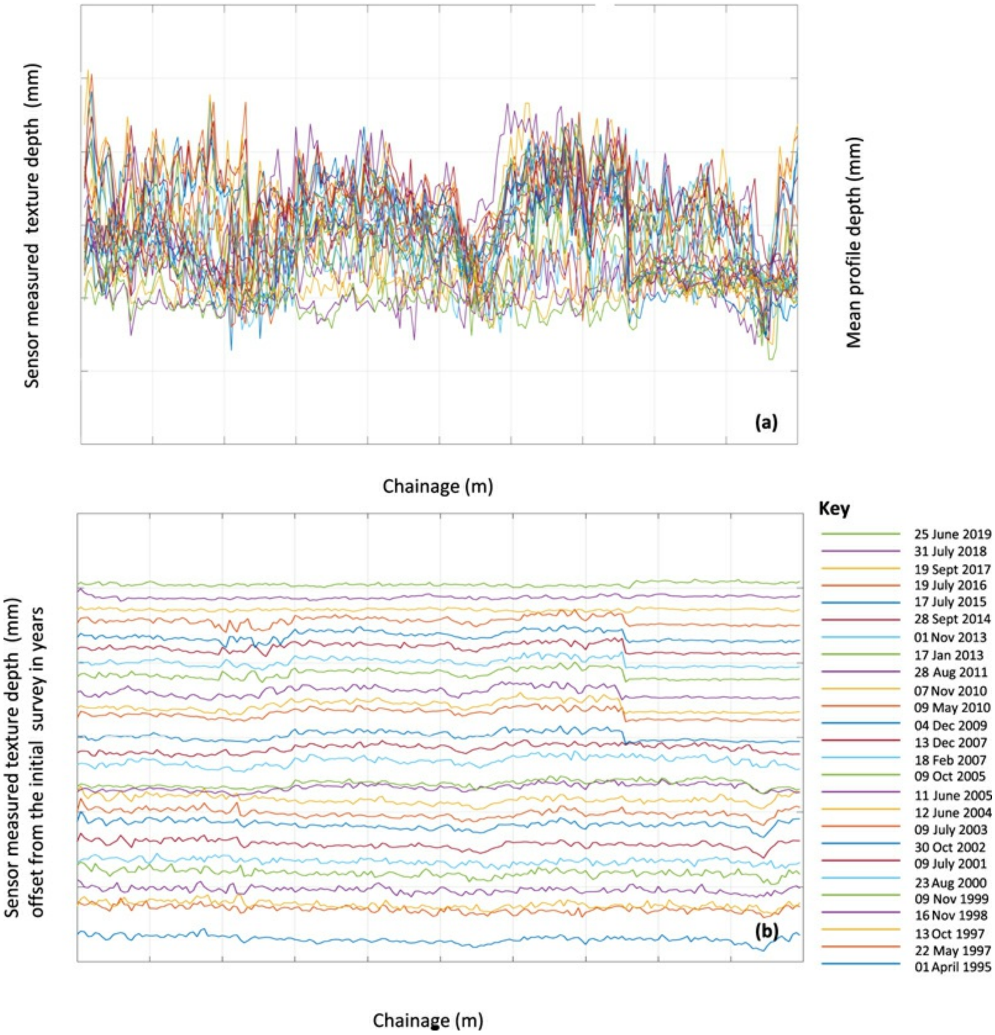
The SMTD data were extracted from HAPMS for the different surveys completed over the 24-year period, and plotted longitudinally, in time series, in years commencing from the initial survey date for each lane. A low pass zero-phase 0.1 m^{-1} wavenumber filter (Gubbins 2004) was then designed and applied to the SMTD data using MATLAB, to remove high wavenumber (short wavelength) noise from the longitudinal road texture signal. The filtered profiles for each lane have been presented as areal plots with the x-axis as chainage, and the y-axis as a time axis in days from the date of the first survey in the time-lapse sequence. Differencing techniques (Williams 2012) have also been applied to the filtered SMTD data to reveal the change in road surface condition with time. The baseline SMTD data from the initial survey was removed from the later survey results to illustrate change, and cumulative change was also aggregated by finding the mean rate of change in days over each time epoch. The long-term rate of change in SMTD for the surfacing in each lane section was characterised by fitting a linear regression with a 95% prediction interval to scatter plots of SMTD against time in days from the initial survey. Finally, wavenumber amplitude spectra were calculated using a Fast Fourier Transform designed in MATLAB (Bloomfield 2000). The wavenumber amplitude spectra were used to characterise the dominating wavenumbers within the data. Examining the spectra, the dominating wavenumbers occurred within a band of between 0.01 and 0.035 m^{-1}. Consequently, a 0.01–0.03 m^{-1} band-pass wavenumber filter, with a gentle 'roll off' on either side was applied to the filtered SMTD data. This second filter attenuated the high and low wavenumber signals within the SMTD data. The results for each survey date were plotted longitudinally, in time series, in years commencing from the initial survey date.

4. Validating results and discussion

4.1. Filtered Road Texture Time Series Data

The processed SMTD data were validated against maintenance records held in HAPMS for the two lanes. Figure 2(a) shows the SMTD for the different surveys completed over the 24-year period, for which Lane 1 have been plotted in time series (years) from the initial survey date of the 1st April 1995 (refer to Figure 2(b)).

Figure 2. Raw Data: (a) Sensor measured texture depth data for Lane 1 of the northbound route of the M6 motorway in Cumbria, UK. (b) Sensor measured texture depth data represented spatially, in time series, in years.



The low pass zero-phase 0.1 m^{-1} wavenumber filtered SMTD data are shown in Figures 3 and 4 for Lane 1 and Lane 2 respectively. Plotted in time series (days) the data for Lane 1 clearly delineates the construction joints at chainage 600 m (refer Figure 1(d)) and chainage 1500 m (refer to Figure 1(c)). Furthermore, the change in colour of Section 1 from broadly keppel and yellow colour tones to blue just before 4000 days (refer to Figure 3 (i)), and just after 8000 days (refer to Figure 3 (ii)) indicates there has been a marked change in road surfacing. This matches the HAPMS construction records for Lane 1, that confirm a heavy-duty macadam was laid on the 27th August 2004 and a thin mastic asphalt on the 1st October 2006. The change to thin mastic asphalt just after 8000 days is again evident in the colour sequencing extending into Section 2. Similarly, for Section 3, there is a change in colour tones between typically cyan shades to deep blue at a time epoch 5000 days. This is again validated by the HAPMS construction records, which record that a thin polymer surfacing was laid at this location on the 3rd March 2008. Universally, the spatially plotted filtered SMTD data was shown 'roughing-up' or having increased texture depth through the lifetime of each surface, with plot colours progressing to become more yellow with time prior to resurfacing. A general trend of increase in SMTD in this manner matches the recent findings of Plati and Pomoni (2019).

Figure 3. 0.1 m^{-1} Wavenumber Filtered Time Series Sensor Measured Texture Data Lane 1: (i) indicates a change in road surfacing after the 12th June 2004 survey date. (ii) indicates a change in road surfacing after the 19th July 2016 survey date. (ii) indicates a change in road surfacing after the 13th December 2007 survey date.

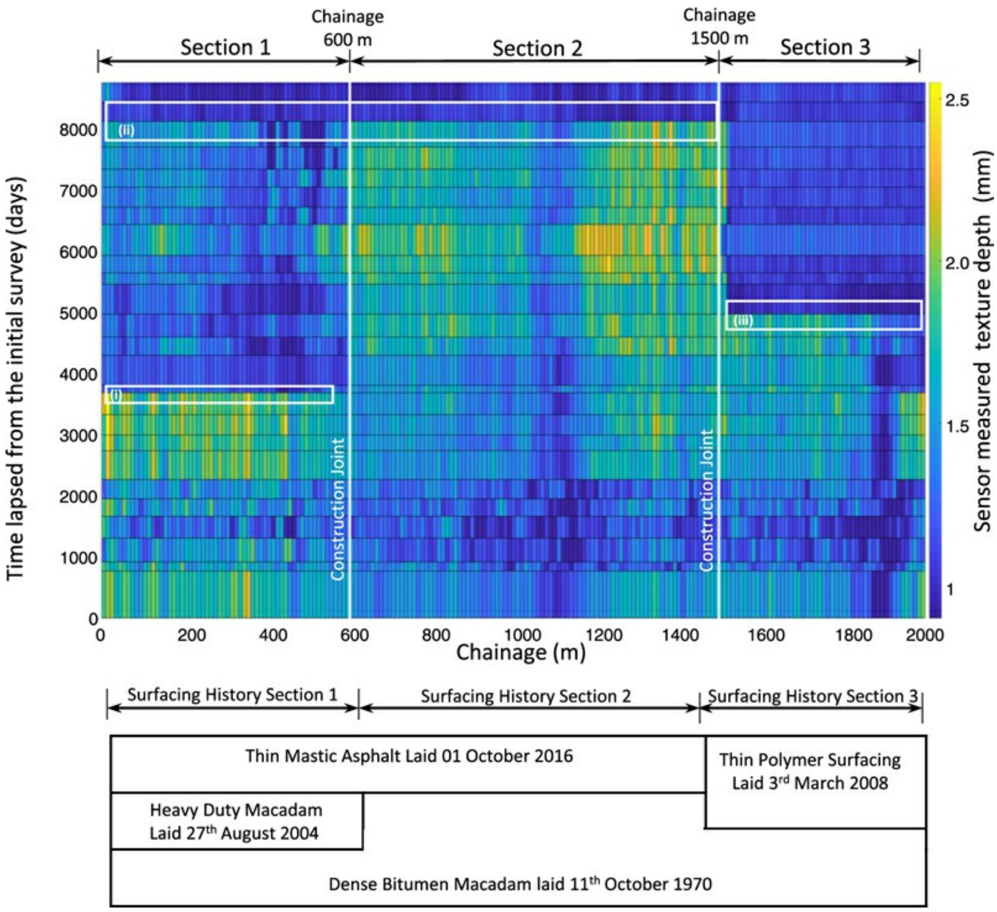
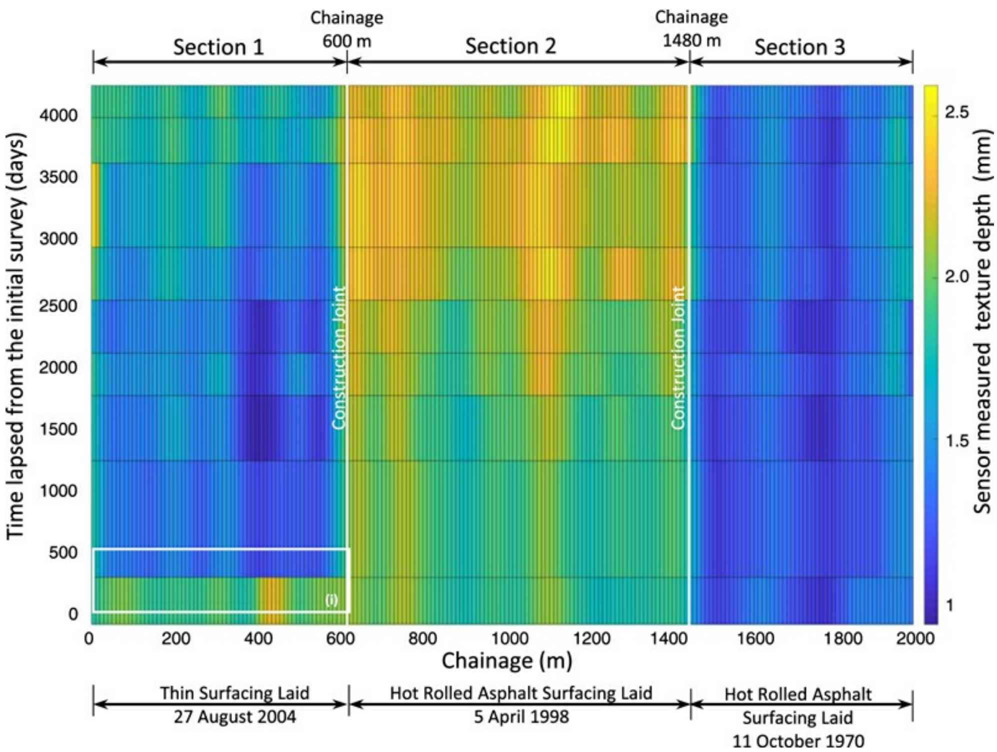


Figure 4. 0.1 m^{-1} Wavenumber Filtered Time Series Sensor Measured Texture Data for Lane 2. (i) indicates a change in road surfacing after the first survey date 12th June 2004.



Correspondingly, for Lane 2 of the M6 motorway, the low pass zero-phase 0.1 m^{-1} wavenumber filtered SMTD data clearly indicate that the road texture is increasing in roughness with the passage of time for Section 1 and Section 2. Section 1 demonstrates a typical increase in road texture from 1.5 mm to 2 mm, and Section 2, 2.0–2.5 mm respectively. In a similar manner Section 3 (refer to Figure 4) of Lane 2 demonstrates some increase in roughness from the 2000 days epoch, starting at approximately chainage 1900 m, with road texture increasing from typically 1.6 to 1.9 mm. The spatially represented data depict the construction joints at chainage 600 m and chainage 1480 m shown in Figure 1(c) and (d). Additionally, the change in colour of Section 1 (refer to Figure 4) of the road, from predominately turquoise (representing road texture of 2 mm) to blue (representing road texture of 1.2 mm) between the zero and 500 days epoch, indicates that there has been a change in road surfacing between the first survey and the second survey on 11th June 2005 (refer to Figure 4 (i)). This is consistent with both the construction records for this section of the road that state a thin surfacing was laid on the 27th August 2004, and the localised patch repairs to the highway surface found in this location (refer to Figure 1(d)). The Section 3 of the lane (refer to Figure 4), does not appear to have experienced as much road texture wear as the Section 1 or 2. Again, this matches the road conditions found in the field, with the HRA road surface after the construction joint at chainage 1480 m laid at a different date to the HRA between chainage 600 and 1480 m (refer to Figure 1(c)).

The HRA between chainage 600 and 1480 m forms a climbing gradient section of the motorway, ascending uphill towards the summit of a fell in Cumbria. The uphill section of the motorway receives slower moving traffic, as trucks and articulated vehicles climb to the fell crest, and consequently the HRA road surface is likely to experience sustain greater loading with the probable result of an increased rate of texture change (refer to Figure 4(b)). The SMTD of the HRA between chainage 600 and 1480 m (Section 2) is reported as being deeper, typically 2–2.5 mm, than the adjacent Section 3 comprised of HRA, where SMTD is typically between 1 and 1.5 mm (refer to Figure 3). The increase in the SMTD within Section 2 of the study length might indicate a condition failure of the surface, fretting for example may increase texture depth if gaps left by the lost aggregates form a higher overall texture than with the stones present. Finally, the difference in texture between Section 2 and 3 might be attributed to variability in the bitumen penetration index or binder mix between the two road sections (Wu et al. 2012). The bitumen binder mix influences pavement stiffness, and can harden with exposure to oxygen and different temperature effects, contributing to variability in the deterioration of the pavement (Visscher and Vanelstraete 2017). Overall, the results demonstrate that it is possible for the filtered SMTD time series to be plotted spatially and used effectively to visually observe segments of a road surface which are changing at different rates. Within Section 2 of the Lane 2 the changing SMTD appears as yellow bands, which widen progressively with the passage of time. This advance presents the potential for future research to explore the use of visual recognition software to identify 'change traces' and establish if they coincide with areas of poor pavement condition in order to improve pavement management systems.

4.2. Road texture change data

The mean cumulative change of SMTD for all the sections of the 2 km study length are shown on Figure 5(b) for Lane 1 and Figure 6(b) Lane 2. The mean cumulative change has been plotted spatially against the time lapsed from the initial survey, in days for each lane. The plots reveal the changes in surfacing that have occurred in each lane through time and the location of the construction joints. The figures confirm that the new analysis method make it possible to track the change in SMTD over time, generating useful monitoring data for pavement management systems and underpinning highway maintenance decisions. A long-term rate of change for each section of lane has been characterised by fitting a linear regression with 95% prediction interval to scatter plots of SMTD against time in days from the initial survey (refer to Figure 5(c) and Figure 6(c)). The long-term rate of change is distinct from the evolution of surface texture, characterised spatially on the 0.1 m^{-1} wavenumber filtered times series SMTD data plots (refer to Figure 3 and Figure 4). In Lane 2 the thin surfacing of Section 1 demonstrates the most rapid rate of long-term change at 1.301×10^{-4} mm/day, this might be expected because thin surfacing represents a surface rejuvenation technique and is known by road managers to have a shorter service life. In Lane 2 the HRA in Section 2 is changing at 1.021×10^{-4} mm/day, a long-term rate 328% faster than Section 3 at 0.311×10^{-4} mm/day over the same time period of 4122 days. Section 2 is an uphill climbing section and is likely to experience sustained greater loading from slower climbing vehicles leading to increased change. Interestingly, in Lane 1 the long-term rate of change for the DBM in the uphill climbing section of Section 2 is 0.787×10^{-4} mm/day, and in contrast to Lane 2, is less than Section 3 at 1.021×10^{-4} mm/day. However, the long-term rate of change for Section 2 is influenced by the time epoch for section. The DBM remained in-situ as a highway surfacing for 7780 days from the first survey in Section 2, 67% longer than the DBM surfacing in Section 3 which was replaced after 4639 days. Assessed over the same 4639 d epoch, the long-term rate of change of Section 2 is 1.063×10^{-4} mm/day, which is 4% faster than Section 3, suggesting that that uphill and downhill sections of DBM were wearing at largely the same rate. The DBM in Section 2 Lane 1 is also changing more slowly than the HRA in the same section in Lane 2. The DBM is in the nearside land of the motorway, which is generally accepted to receive a higher proportion of slow-moving heavy vehicles. The slower rate of wear might indicate that the negative texture of the DBM is more favourable to climbing sections of road than HRA long-term, but further research of surfacing of comparable age, over the same epoch would be required at a number of sites to establish if this is the case. Being able to categorise a linear rate of change has unlocked the potential to develop a method for forecasting the future long-term rate of change of SMTD by extrapolation, for highway surfaces at discrete lane locations upon a road network. Thus, enabling legacy data collected annually for 7000 km of the UK Strategic Road Network, relating to SMTD, to be used in predictive planning of texture depth thresholds for essential road repair (Design Manual for Roads and Bridges 2008, and 2015). Further developing, this method would need to take account of potentially non-linear variables influencing future road conditions such as traffic volumes and weather patterns. Additionally, the long-term rate of change of SMTD might feasibly be adapted to estimate skid resistance in the manner of Plati and Pomoni (2019), were available data enables the minimum cumulative traffic threshold to be established.

Figure 5. Lane 1 Rate of Change of Road Texture With Time: (a) A difference plot of the sensor measured texture depth data for Section 2 of Lane 1. (b) Mean cumulative change in sensor measured texture depth for Lane 1. (c) The change in

sensor measured texture depth with time for Section 2 of Lane 1. (i) A linear regression line illustrates the rate of change in sensor measured texture depth. (ii) The 95 percent prediction interval.

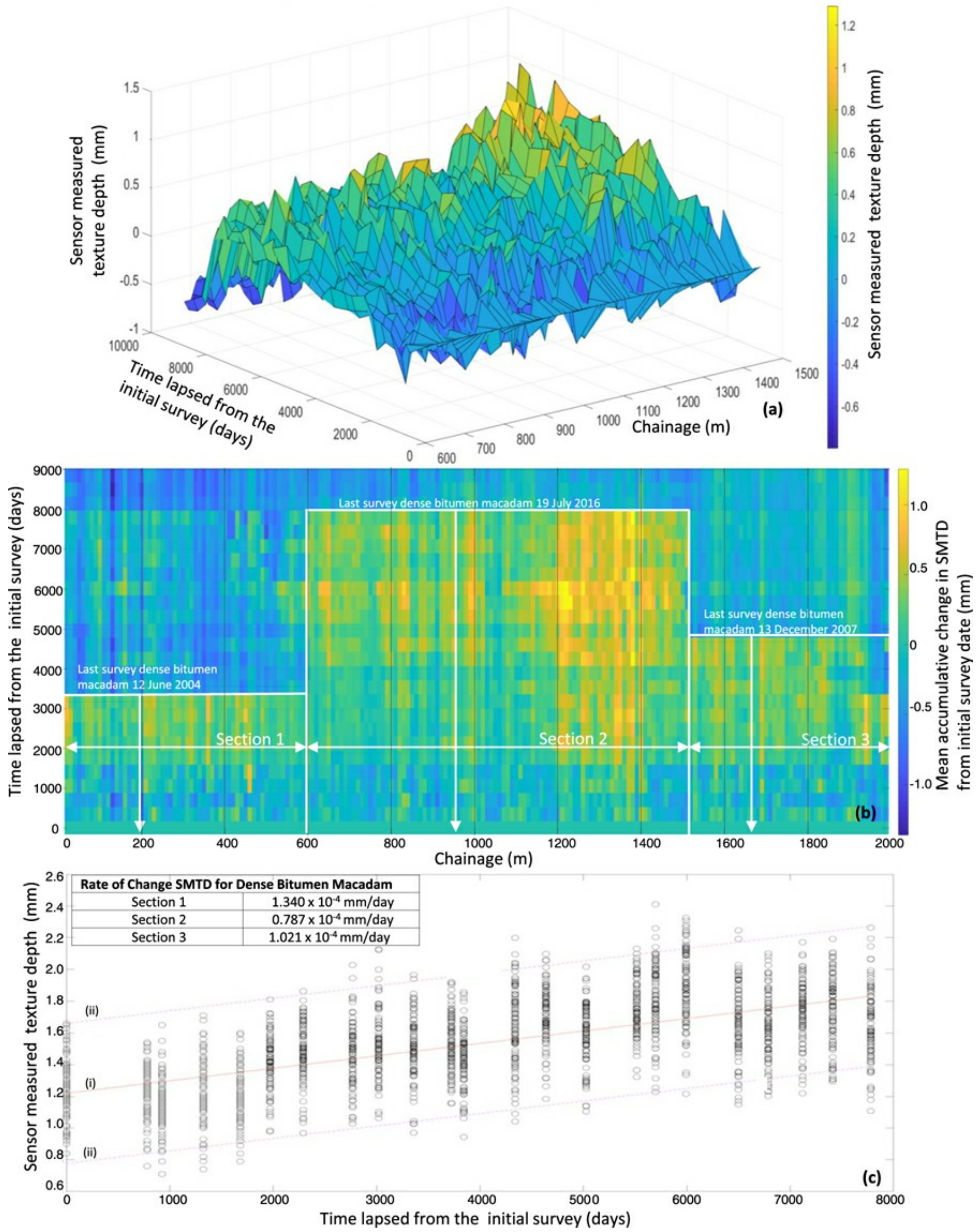
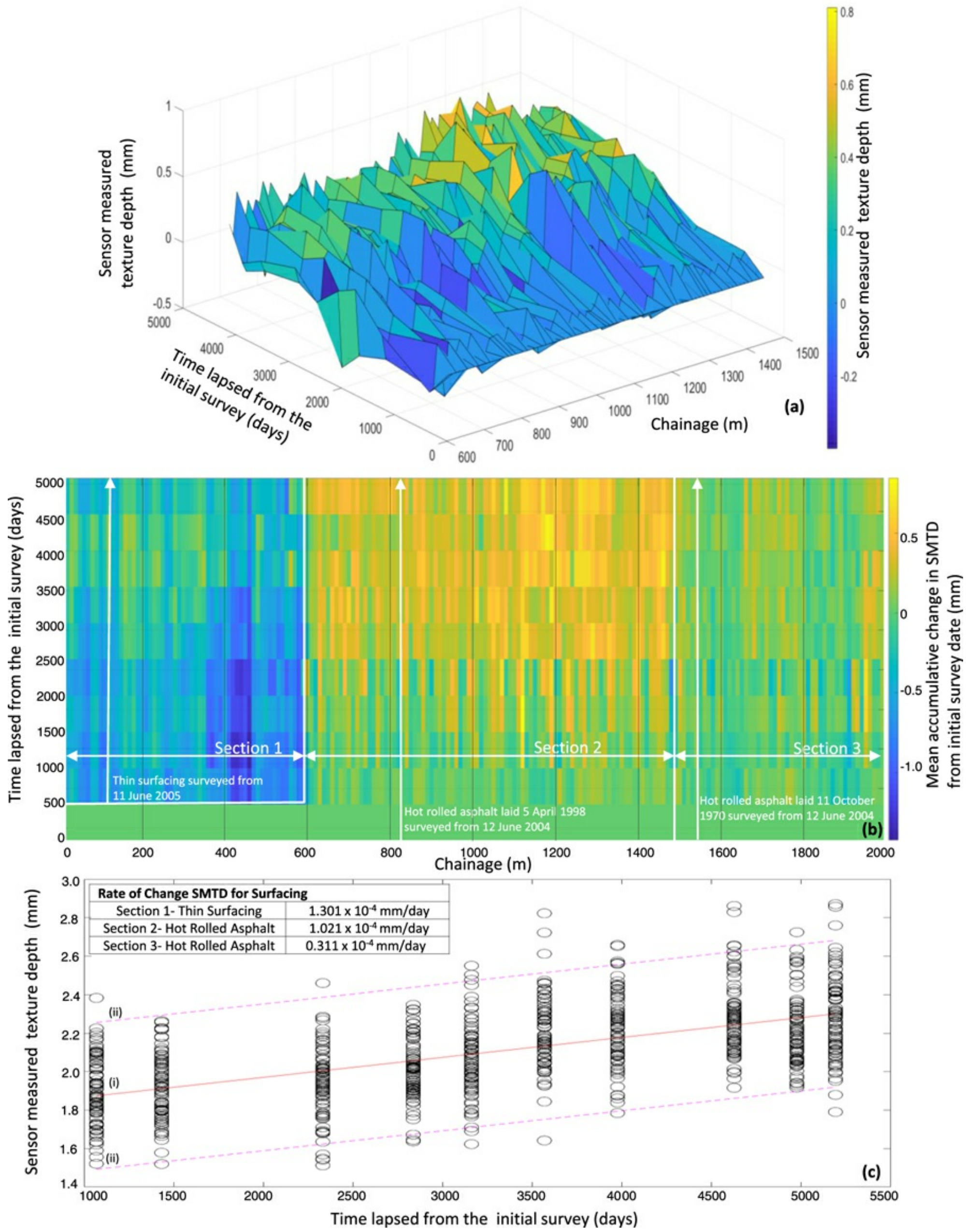


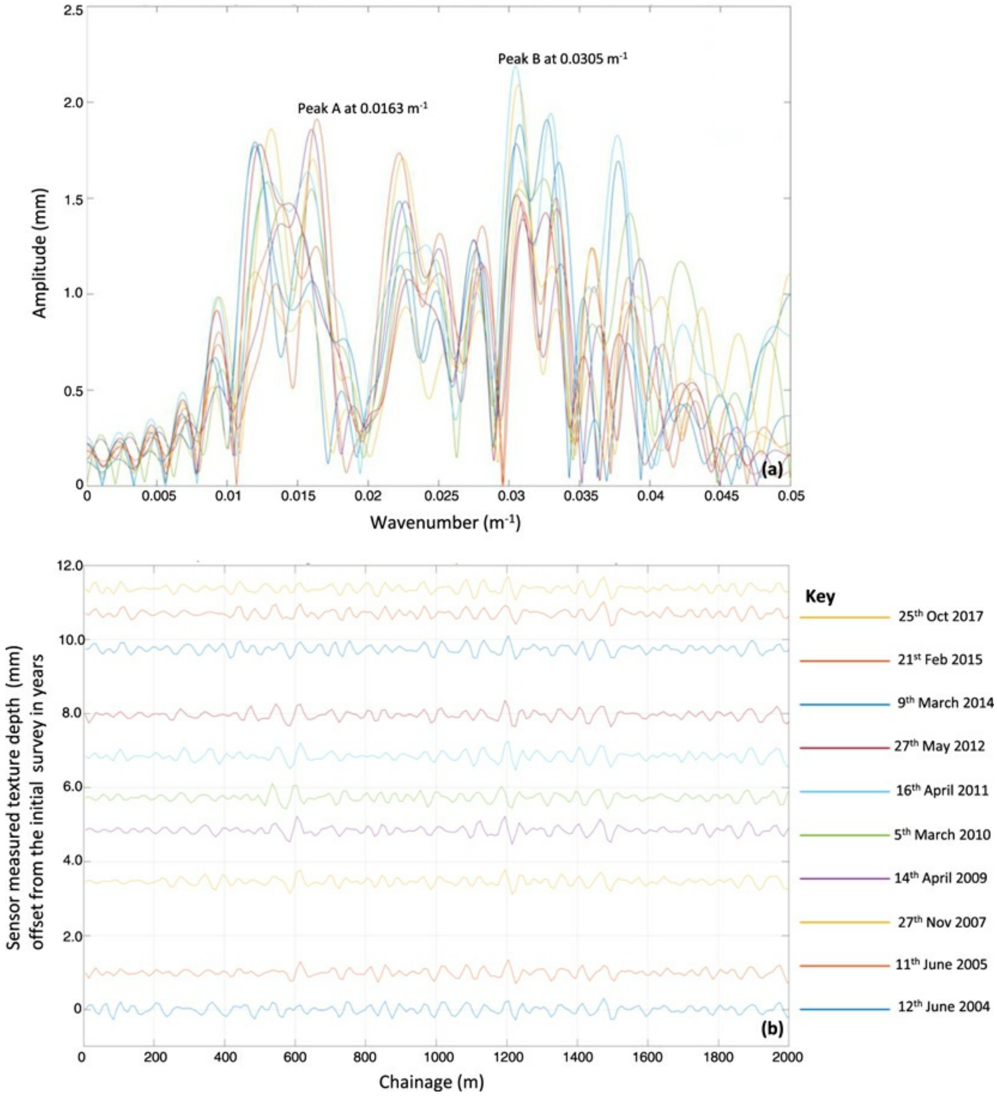
Figure 6. Lane 2 Rate of Change of Road Texture With Time: (a) A difference plot of the sensor measured texture depth data for Section 2 of Lane 2. (b) Mean cumulative change in sensor measured texture for Lane 2. (c) The change in sensor measured texture depth with time for Section 2 of Lane 2 (i) A linear regression line illustrates the rate of change in sensor measured texture depth. (ii) The 95 percent prediction interval.



4.3 . Road spectra analysis data

A difference plot of the SMTD data for Section 2 of Lane 1 and Lane 2 (refer to Figure 5(a) and Figure 6(a)) confirms the findings from the filtered time series SMTD data and mean cumulative SMTD change graph, further illustrating the change in road surface condition with time. It is evident that the SMTD becomes rougher with time, and that wavenumber signal also grows larger. Additionally, there is a clear periodicity to the wavenumber signal, represented by the regular sinusoidal signal of the road texture. Greater SMTD change occurs at the peaks of the sinusoidal wave as opposed to the troughs. The amplitude of the periodicity changes at chainage 600 and 1480 m suggesting that the spaced changes in pavement texture might be triggered as a moving vehicle's suspension passes across a construction joint. Wavenumber amplitude spectra of the SMTD data calculated using a Fast Fourier Transform characterises the periodicity of the sinusoidal wavenumber signal observed in the difference plot (refer to Figure 7(a)). The wavenumber spectra have three clear bimodal shape peaks occurring between wavenumber 0.01–0.035 m^{-1} respectively, demonstrating that the signal is dominated by wavelengths within this wavenumber banding. Accordingly, a 0.01–0.03 m^{-1} band-pass wavenumber filter was applied to the

Figure 7. Spectra Analysis and Band Pass Filtered Data: (a) A 0.1 m^{-1} wavenumber low pass 1D spectral analysis of the sensor measured texture depth data for Section 3 Lane 2 (b) A 0.01–0.03 m^{-1} band pass wavenumber filter with a gentle 'roll off' on either side has been applied to the sensor measure texture depth data for Lane 2.

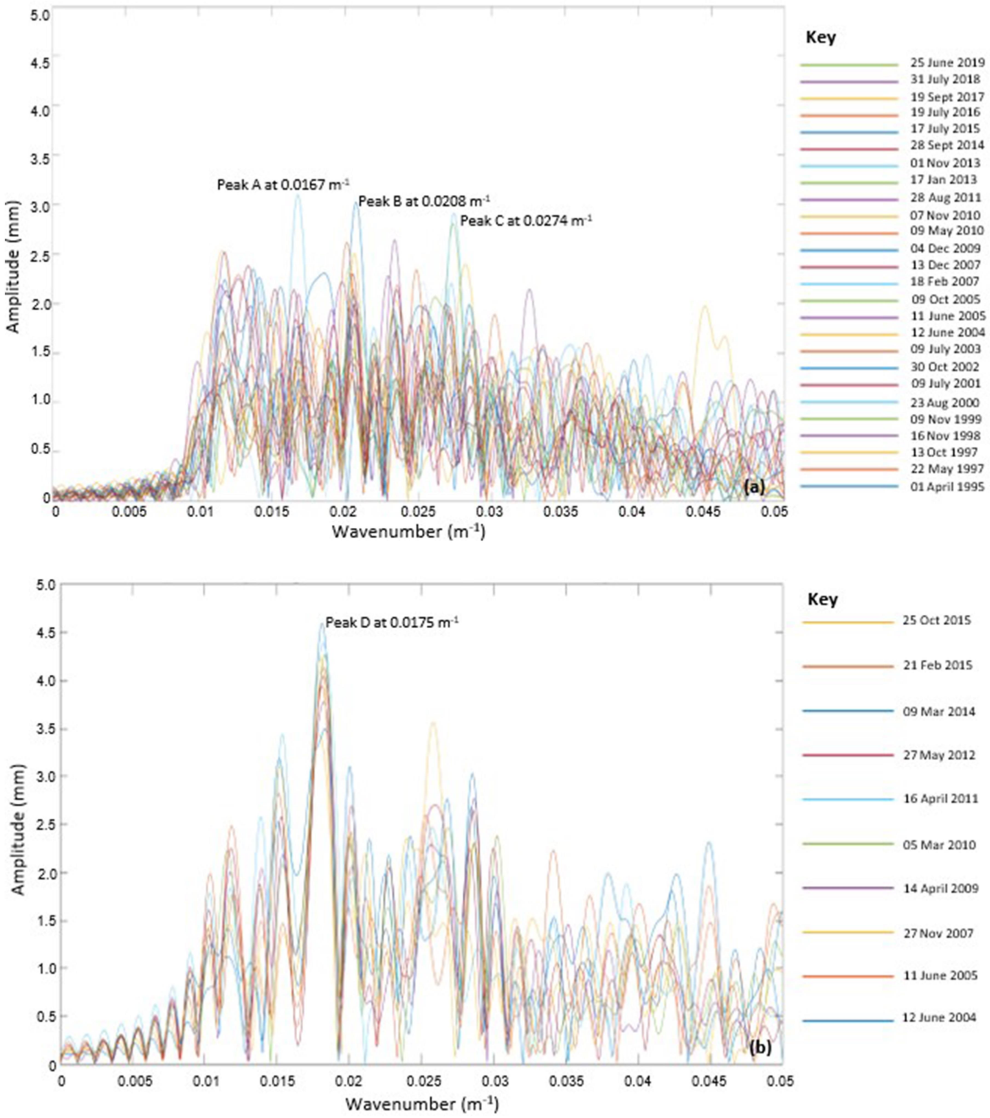


SMTD data to attenuated the high and low frequency wavenumber signals within the raw data. Figure 7(b) illustrates the band-pass filtered SMTD data for each survey represented temporally on the y-axis, in time series, in years commencing from the initial survey date of the 12th June 2004. The filtered data have a periodicity extending systematically through the 11 years of survey data analysed. The invariant nature of the periodicity through time suggests that the unevenness might be constructed into the road (possibly as a consequence of the use of highway paving plant), or perhaps imprinted during its early history after construction.

The periodicity is associated with a wavelength typically of between 33 and 62 m, which represent the location of the two highest peaks (Peak A and Peak B, Figure 7(a)) of the spectral analysis at wavenumbers of 0.0163 and 0.0305 m^{-1}. It is known that the suspension systems of heavy vehicles such as a buses and trucks apply a cyclic loading to a pavement surface via the tyre-road interaction. The suspension system of a large vehicle such as a bus, can be simplified to a spring-mass-dashpot model and for a bus has previously been shown to have a resonance frequency of around 0.5 Hz (Sekuic and Dedovic 2011). At this resonance, the tyres of a vehicle travelling at a speed of 96.56 km/h would apply a cyclic load to a pavement surface with a wavelength of 53.6 m. On climbing sections of motorway, heavy vehicles such as trucks or buses tend to travel more slowly, and this would shorten the distance between the application of each tyre load; for example at 72.42 km/h a truck or bus with a suspension system operating at 0.5 Hz would apply a load every 40 m. As the periodicity observed at the study site was banded with wavelength between 33 and 62 m, a plausible causation theory is that the cyclic loading of heavy vehicle suspension systems has imprinted the undulating wavelengths into the road surface early in the road's life. Imprinting may have arisen through a process of the intermittent-localised compaction of the lower pavement layers or the pavement surface when the bitumen matrix becomes marginally softer in the warmth of the summer. The periodic features observed are systematically well-organised, meaning that the heavy vehicles such as trucks or buses would have to be in phase with each other when driving along the pavement surface, which is what would be expected. Synchronisation of traffic flow is a recognised phenomenon (Kerner 2018) and in phase movement of vehicle suspension in traffic flow could be triggered by an irregularity such as a bump or more likely a construction joint within the road. Indeed, Figure 7(b) shows a step in the periodicity features occurring at both chainage 600 m and chainage 1480 m, which coincide with known construction joints for Lane 2. Conceivably, the construction joints act as triggers at consistent points on the route, exciting high amplitude resonances within the suspension systems of the travelling vehicles and leading them to move up and down in phase with each other. Subsequent change in the pavement surface through compaction arising from the cyclic tyre load, would reinforce the resonant excitation of the heavy vehicle and thus maintain them in phase with one another. The proposed influence of the cyclic tyre loading action of the heavy vehicles to the pavement is supported by Figure 5(a) and Figure 6(a) which shows change of SMTD generally coinciding with the peaks of the periodicity features, and this change being amplified with time suggesting consistent and progressive tyre-pavement interaction at these locations.

The influence of trafficking on the development of SMTD upon a road surface is further illustrated by comparing the wavenumber amplitude spectra for Section 2 of Lane 1 and Lane 2 (refer to Figure 8(a,b), respectively). Lane 1 clearly contains more signal frequencies than Lane 2 demonstrating a greater mix of vehicle loading conditions in the more congested nearside lane of the motorway, arising from cars and heavy goods vehicles travelling at different speeds. The amplitude of the wavenumber spectra signal rises steeply at 0.01^{-1} m delineating the start of the dominance of wavelengths at 100 m. Cars have been shown to have a resonance frequency of between 1 and 2 Hz (Barbosa, 2012). A car travelling at 144.84 km/h, a typical speeding velocity for a performance vehicle in the UK, with a median frequency of 1.4 Hz, will have a wavelength of 100 m. Figure 8(a) has three dominant peaks; Peak A at 0.0167 m^{-1} and Peak B at 0.0208 m^{-1} correspond to wavelengths of 60 and 48.2 m respectively. These signals might be introduced to the SMTD as discussed before by a heavy vehicle with a resonance frequency of 0.5 Hz travelling between 86.76 and 108 km/h. The Peak C at 0.0274 m^{-1} matches a wavelength of 36.4 m and equates to a car travelling at 131 km/hr again with a resonance frequency of 1.4 Hz. The comparison of wavenumber amplitude spectra reinforces the potential effect of cyclic tyre load action on the highway surface by different vehicle types. The influence of cyclic tyre load action from the initial findings of this studying characterising dominant wavelengths and discovering a periodicity in SMTD, suggest that further research in this field is warranted. If vehicle suspension systems are found to influence texture evolution through cyclic tyre loading, then this will have implications for the future design of highway pavements.

Figure 8. Comparison of Spectra Analysis Data for Section 2 of Lane 1 and Lane 2: (a) A 0.1 m^{-1} Wavenumber low pass 1D spectral analysis of the sensor measured texture depth data for Section 2 Lane 1. (b) A 0.1 m^{-1} wavenumber low pass 1D spectral analysis of the sensor measured texture depth data for Section 2 Lane 2.



5. Conclusions

In conclusion, the paper has provided rare and a valuable long-term study of SMTD. A new computational process has been developed and applied to reveal a number of key and important trends influencing long term change in pavement texture as follows:

- It is possible for wavenumber filtered SMTD time series time-lapse data to be used to visually observe discrete segments of a road surface which are changing with time
- Change 'traces' are evident within the wavenumber filtered SMTD time series. This presents the potential for further research to use visual recognition software to identify change 'traces' in order to locate areas of poor pavement condition.
- The study presents a viable method to track the rate of change of SMTD over time, generating essential monitoring data for pavement management systems and highway maintenance decisions.
- The long-term rate of change in SMTD could be used to predict the useful working life of a pavement surface and to predict when maintenance or preventative interventions will be necessary.
- At unevenness scale a periodicity is observable in the data systematically through time, suggesting that unevenness might be imprinted into a road surface during construction or early in its life.
- A plausible theoretical cause of the observed unevenness periodicity is that it is 'imprinted' in the early life of the pavement. 'Imprinting' may occur as a consequence of cyclic tyre loading applied by the suspension systems of heavy vehicles.
- Construction joints in pavement surfaces, in combination with vehicle travel speeds, have the potential to trigger periodically spaced change in pavement texture.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

ASTM International. 2015. ASTM E1926-08: 2015. *Standard practice for computing International Roughness Index of roads from longitudinal profile measurements*, West Conshohocken [Online] Available from: https://www.astm.org/Standards/E1926 [Accessed 18 Aug 2019].

Barbosa, R.S, 2012. Vehicle vibration response subjected to longwave measured pavement irregularity. *Journal of Mechanical Engineering and Automation*, 2 (2), 17–24. doi:10.5923/j.jmea.20120202.04.

Bloomfield, P, 2000. *Fourier analysis of time series: An introduction*. New York: Wiley-InterScience. ISBN-10:0471889482.

Cunto, F.J.C., and Branco, V.T.F.C, 2016. Influence of Skid Resistance in Microscopic Simulate Traffic Conflict. *In: 17th International Conference Road Safety on Five Continents Conference*, 17th–19th May 2016 Rio de Janeiro, Brazil [Online] Available from: http://vti.diva-portal.org/smash/get/diva2:926094/FULLTEXT01.pdf.

Department for Transport. 2012. Guidance on Road Classification and Primary Route Network. Great Britain. London, [Online] Available from: https://www.geoplace.co.uk/documents/10181/87438/Guidance+on+Road+Classification+and+the+Primary+Route+Network/b7144810-af9a-41a1-a4cf-0f9c6de015d4 (Accessed 10th May 2020).

Department for Transport. 2019. Technical Note: Version 1.4, 03.10.19. *Road Condition and Maintenance Data*. Great Britain. London, [Online] Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775107/road-conditions-technote.pdf (Accessed 11th August 2019).

Design Manual for Roads and Bridges. 2008. HD29/08: Volume 7, Section 3, Part 2: *Data for Pavement Assessment*. Norwich: The Stationary Office, Office of Public Sector Information. [Online] Available from: http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol7/section3/hd2908.pdf (Accessed 11th August 2019).

Design Manual for Roads and Bridges. 2015. HD28/15: Volume 7, Section 3, Part 1: *Skid Resistance*. Norwich: The Stationary Office, Office of Public Sector Information. [Online] Available from: http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol7/section3/hd2815.pdf (Accessed 11th August 2019).

Ejsmont, J., et al., 2017. Road texture influence on tyre rolling resistance. *Road Materials and Pavement Design*, 18 (1), 181–198. doi:10.1080/14680629.2016.1160835.

European Collaborative Project. 2014. *Tomorrow's Road Infrastructure Monitoring and Management- Final Summary Report*. Sweden:

European Collaborative Project, FP7-285119 (7th RTD Framework Programme) [online]. Available from: https://trimis.ec.europa.eu/sites/default/files/project/documents/9751/final1-trimm-d5-3-finalreport2014-to-print.pdf (Accessed 13th August 2019).

European Committee for Standardisation. 2017. prEN 13036-5: *Road and airfield surface characteristics – Test methods: Part 5: Determination of longitudinal unevenness indices*. Brussels: Comite Europeen de Normalisation. [Online] Available from: https://infostore.saiglobal.com/en-gb/Standards/PREN-13036-5-DRAFT-2017-342626_SAIG_CEN_CEN_784565/ (Accessed 11th August 2019).

FSV-Austrian Transport Research Association. 2008. COST 354 Performance Indicators for Road Pavements – Final Report. Vennia: Austria, ISBN 978-3-200-01238-7 [Online] Available from: http://cost354.zag.si/fileadmin/cost354/1fr/COST354_FinalReport_05062008.pdf (Accessed 9th January 2020).

Gubbins, D, 2004. *Time series analysis and inverse theory for Geophysicists*. Cambridge: Cambridge University Press. ISBN-10:0521819652.

Highways England. 2019. *Network Management* [Online] Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800964/Network_management.pdf Accessed 11th August 2019.

Hong, S.J., Park, S.W., and Lee, S.W, 2018. Tire-pavement noise prediction using pavement texture. *KSCE Journal of Civil Engineering*, 22 (9), 3358–3362. doi:10.1007/s12205-018-9501-3.

International Organization for Standardization. 2009. ISO 13473-5: 2009 (en) *Characterisation of pavement texture by the use of surface profiles – Part 5: Determination of megatexture*. Geneva, Switzerland: International Organization for Standardization [Online] Available from: https://www.iso.org/obp/ui/#iso:std:iso:13473:-5:ed-1:v1:en (Accessed 11th August 2019).

International Organization for Standardization. 2016. ISO 8608: 2016 *Mechanical Vibration – Road Surface Profiles – Reporting of Measured Data*, Geneva, Switzerland: International Organization for Standardization [Online] Available from: https://www.iso.org/standard/71202.html (Accessed 11th August 2019).

International Organization for Standardization. 2019. ISO 13473-1: 2019 Characterisation of pavement texture by the use of surface profiles – Part 1: determination of mean profile depth. Geneva, Switzerland: International Organization for Standardization [Online] Available from https://www.iso.org/obp/ui/#iso:std:iso:13473:-1:ed-2:v1:en (Accessed 11th August 2019).

Kane, M., and Edmondson, V, 2018. Modelling the bitumen scour effect: Enhancement of a dynamic friction model to predict the skid resistance of rubber upon asphalt surfaces subject to wear by traffic polishing. *Wear*, 400–401, 100–110. doi:10.1016/j.wear.2017.12.013.

Kerner, B.S, 2018. Autonomous driving in framework of three-phase traffic theory. *In: The 7th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS-2018)*, Procedia Computer Science 130, 785–790. https://doi.org/10.1016/j.procs.2018.04.136.

Khasawneh, M., Samadi, M., and Zelelew, H., 2016. Investigation of the factors influencing wavelet-based macrotexture values for HMA pavements. *Road Materials and Pavement Design*, 17 (3), 779–791. doi:10.1080/14680629.2015.1120229.

Klüppel, M., and Heinrich, G, 2001. Rubber friction on Self Affine road Tracks. *Rubber Chemistry and Technology*, 73, 578–606. doi:10.5254/1.3547607.

Kogbara, R.B., et al., 2016. A state-of-the-art review of parameters influencing the measurement and modelling of skid resistance of asphalt pavements. *Construction and Building Materials*, 114, 602–617. doi:10.1016/j.conbuildmat.2016.04.002.

Loprencipe, G., Zoccalli, P., and Cantisani, G, 2019. Effects of vehicular speed on the assessment of pavement road roughness. *Applied Science*, 9 (1783), 1–18. doi:10.3390/app9091783.

Manual of Contract Documents for Highway Works. 2019. Volume 1, Series 900, Clause 942: *Specification for highway Works*. Norwich: The Stationary Office, Office of Public Sector Information. [Online] Available from: http://www.standardsforhighways.co.uk/ha/standards/mchw/vol1/pdfs/2989369_MCHW_Vol1_Series_900_v2.pdf (Accessed 11th August 2019).

Masad, E., et al., 2009. *Prediction asphalt mixture skid resistance based on aggregate characteristics*. Texas: Department of Transportation and Federal Highway Administration. [Online] Available from: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-5627-1.pdf (Accessed 20th May 2020).

Mauro, A.D., Greco, M., and Grimaldi, M, 2016. A Formal Definition of Big data based on its essential features. *Library Review*, 65 (3), 122–135. doi:10.1108/LR-06-2015-0061**[Q3]**.

Meegoda, J.N., and Gao, S, 2015. Evaluation of pavement skid resistance using high speed textile measurements. *Journal of Traffic and Transportation*, 2 (6), 382–390. doi:10.1016/j.jtte.2015.09.001.

Moore, D.F, 1975. *The friction of Pneumatic tyres*. New York: Elsevier. ISBN 0444413235.

Mucka, P, 2017. International roughness index specifications around the world. *Road Materials and Pavement Designs*, 18 (4), 929–965. doi:10.1080/14680629.2016.1197144.

Mucka, P, 2018. Simulated road profiles according to ISO 8608 in vibration analysis. *Journal of Testing and Evaluation*, 46 (1), 405–418. doi:10.1520/JTE20160265.

O'Brien, J. P., and Haddock, J. E, 2009. Frictional resistance of aggregates for hot-mix asphalt pavements (Final Report (FHWA/IN/JTRP-2004/23)). Joint Transportation Research Programme (JTRP) and Purdue University, Indiana Department of Transportation https://doi.org/10.5703/1288284314215.

Organization for Economic Co-operation and Development. 2001. *Asset Management for the Roads Sector Transport*. Paris: France, OCED Publication Service [Online] Available from: https://www.itf-oecd.org/sites/default/files/docs/01assete.pdf (Accessed 9th January 2020).

Persson, B.N.J, 2001. *Sliding friction: Physical principles and Applications*. Berlin: Springer-Verlag. ISBN 978-3-662-04283-0.

Plati, C., and Pomoni, M, 2019. Impact of traffic Volume on pavement macrotexture and skid resistance long-term performance. *Journal of Transportation Research Board*, 2763 (2), 314–322. doi:10.1177/0361198118821343.

Ragland, D. R., Mi Oh, S., and Chan, C.Y, 2010. Evaluation of Traffic and Environment Effects on Skid Resistance and Safety Performance of Rubberized Open-Grade AsphaltConcrete. Research Report: UCB-ITS-PRR-2010-14. California PATH Program, Institute of Transportation Studies, University of California, Berkley, CA [Online] Available from: https://safetrec.berkeley.edu/sites/default/files/publications/evaluation_of_traffic_and_enviornment_effects.pdf (Accessed 10th May 2020).

Rainsford, S., and Parkman, C., ND. *Predicting texture deficiency in pavement management*. NWH NZ Ltd: Transit New Zealand [Online] Available from: http://saferroadsconference.com/wp-content/uploads/2016/05/5-PARKMAN-C-Predicting-textureFP.pdf (Accessed 7th January 2020).

Sayers, M.W., Gillespie, T.D., and Paterson, W.D.O, 1986. Technical Paper Number 46: *Guidelines for conducting and calibrating road roughness measurements*, Washington DC, The World Bank (1986) [Online] Available from: https://deepblue.lib.umich.edu/bitstream/handle/2027.42/3133/72764.pdf?sequence=2&isAllowed=y (Accessed 18th August 2019).

Sekuic, D., and Dedovic, V, 2011. The effects of stiffness and damping on the suspension system elements on the optimisation of the vibrational behaviour of a bus. *International Journal of Traffic and Transportation Engineering*, 1 (4), 231–244. [Online] Available from: https://trid.trb.org/view.aspx?id=1127006 (Accessed 13th January 2020).

Transport Research Board. 2016. *HCM6-16 Highway Capacity Manual A guide for Multimodal Mobility Analysis*. 6th ed. USA: Transport Research Board. ISBN-10 0309369975.

Transport Research Laboratory. 2006. TRL Published Project Report PPR148*: Surface Texture Measurement on Local Roads*, Crowthorne: TRL. [Online] Available from https://trl.co.uk/reports/PPR148 (Accessed 11th August 2019).

UK Government. 2019. Highways England's Pavement Management System Network Layer [Online] Available from https://data.gov.uk/dataset/2b0dd22d-213e-4f5b-99da-8b5ec409112c/highways-england-pavement-management-system-network-layer (Accessed 10th May 2020).

Vaiana, R., et al., 2012. Pavement Surface Performances: an Experimental Application. SIIV – 5th International Congress – Sustainability of Road Infrastructures. In Procedia – Social and Behavioral Sciences. 53, 1151–1162. https://doi.org/10.1016/j.sbspro.2012.09.964.

Visscher, J., and Vanelstraete, A, 2017. Ravelling by traffic: performance testing and field validation. *International Journal of Pavement Research and Technology*, 10 (1), 54–61. doi:10.1016/j.ijprt.2016.12.004.

Williams, R.D., 2012. Chapter 2, Section 3.2 DEMS of Difference. *In Geomorphology Techniques*, [Online] Available from: https://www.geomorphology.org.uk/sites/default/files/geom_tech_chapters/2.3.2_DEMsOfDifference.pdf.

Wu, S., et al., 2012. Rheological properties for aged bitumen containing ultraviolate light resistant materials. *Construction and Building Materials*, 33, 133–138. doi:10.1016/j.conbuildmat.2012.01.019.

Zhang, D., et al., 2018. Automated pavement detection using 3D laser profiling technology. *Automation in Construction*, 96, 350–365. doi:10.1016/j.autcon.2018.09.019.